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ScienceDirect
Technological Forecasting & Social Change 74 (2007) 873–886
Technological Forecasting and Social Change

Introduction

Integrated assessment of uncertainties in greenhouse gas emissions and their mitigation: Introduction and overview

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Received 20 July 2006; accepted 26 July 2006

Abstract

This paper provides the background and the context for the analyses presented in the seven papers of this Special Issue on Integrated Assessment of Uncertainties in Greenhouse Gas Emissions and their Mitigation. First, the main topic and content of the Special Issue is given, followed by an overall overview. Second, detailed overviews and summaries of the seven papers are given. The specific analytical and methodological features and findings of each paper are highlighted and the linkages between the various papers presented in the Special Issue are provided.

1. Introduction

Climate change and possible response strategies have high scientific and policy relevance but are also associated with major controversies. The time frame of a century or more involved in any analysis of climate change, as well as, the complexity of natural and socio-economic systems and their interactions – all shrouded by deep uncertainties – pose major scientific and policy challenges. There needs to be a shared

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doi:10.1016/j.techfore.2006.07.009

understanding of these challenges in order to come to grips with the possible magnitude and nature of climate change and to craft response strategies. This all makes climate change perhaps one of the most challenging issues to be addressed by interdisciplinary research and by policy measures to date. How will human drivers ranging from the realm of demographics, economics, and technology to social behavior and institutions shape future emissions of greenhouse gases (GHGs)? Are there ways of "bending down" the curve of ever increasing radiative forcing? What will be the consequences of radiative forcing change on global, regional, as well as local climates both in terms of changes in magnitude (e.g., warming, precipitation) as well as in nature (most prominently variability and possibilities of extreme events)? What will be the impacts on natural and human systems of a changing climate? Finally, what are the feasibilities, costs, and benefits (in terms of avoided impacts) of response strategies? These are some of the questions this Special Issue addresses from an integrated and interdisciplinary perspective.

There are sufficient scientific and policy reasons to justify interest in climate change and to devote a full Special Issue to this topic. However, interest in itself needs to be complemented by new analytical and methodological perspectives. The collective objective of the papers presented here is to report and document new methods and findings of the integrated assessment of climate change at the International Institute of Applied Systems Analysis (IIASA) in Laxenburg, Austria.

The main methodological approach for addressing the complex couplings of socio-economic and natural systems that characterize climate change are the so-called integrated assessment frameworks that try to capture the most important linkages and feedbacks through reduced form models of varying complexity and detail. Many readers of this journal will be familiar with this approach, which is an offspring of the "global modeling" of the 1970s in response to perceived "limits to growth". Another methodological avenue explored in climate change analysis has been to complement detailed, disciplinary models, most prominently those of coupled energy–economy systems with reduced form representations of the carbon cycle, global climate change, and its impacts. These models and the cost–benefit analytical paradigm they often employ have generated important insights and have structured much of the climate-change policy debate to date.

The approach reported in the papers of this Special Issue extends the methodological paradigm of integrated assessment models into a broader interdisciplinary integrated assessment based on coupling detailed models of energy and industrial systems, agriculture, and forests. These sectors are both the main emitters of GHGs causing potential climate change, as well as, key targets to implement response strategies.

IIASA is a unique institution in that it provides the blend of disciplinary expertise combined with an interdisciplinary research mission. On first reflection, this might appear to be sufficient for a true system analytical and integrated assessment perspective that climate change requires. Yet, it took a group of dedicated researchers from diverse and interdisciplinary fields such as demographics, technology, energy, agricultural, and forest systems to overcome the customary topical compartmentalization of collaborative research and to establish an institute-wide integrated research effort called the Greenhouse Gas Initiative. The first research results of this integrated interdisciplinary effort are presented in this Special Issue. The research mission of the Greenhouse Gas Initiative is to "link all major research programs of IIASA dealing with areas of climate change and that include both basic as well as applied, policy-relevant research, aiming to assess conditions, uncertainties, impacts as well as policy frameworks for addressing climate stabilization both from a near-term as well as long-term perspective." While in its origins and governance structure the Greenhouse Gas Initiative was a typical "grass-roots" movement, it could only blossom and evolve into a fully integrated research effort because of the support and funding from IIASA's management and governing board, the IIASA Council, which are both gratefully acknowledged here for their continued support and guidance.

2. Common threads connecting the papers in this special issue

The joint objective of the seven papers published in this Special Issue is to explore the feasibility and costs of meeting alternative climate stabilization targets under a range of salient long-term uncertainties. The main and central theme of this Special Issue is uncertainty. Next to the new methodological and organizational approaches in interdisciplinary research ventured by IIASA's Greenhouse Gas Initiative, the papers in this Special Issue also present a new, pluralistic approach to treat uncertainty that combines model sensitivity analysis and probabilistic approaches with scenario-based techniques.

A range of scenarios (called A2r, B1, and B2) and their corresponding climate stabilization variants jointly frame the overall uncertainties. In particular, all papers in this Special Issue explore a set of three clusters of climate change uncertainties. They include uncertainties associated with alternative development paths, with climate impacts and vulnerabilities, and with climate stabilization. The uncertainties of development paths are related to demographic, economic, and technological developments that could lead to high (A2r), intermediary (B2), or low (B1) emissions of GHGs and magnitude of future climate changes, as discussed in the paper by Riahi et al. Uncertainties of climate impacts and vulnerabilities focus primarily on the provision of food and range from high (A2r) to low (B1), as in the papers by Tubiello and Fischer, and Fischer et al. Uncertainties of climate stabilization are addressed by a combination of scenario and model sensitivity analyses where altogether 11 stabilization scenarios for eight comparable stabilization levels ranging from 480 to 1390 ppmv (CO_2-equivalent concentration for all GHGs taken together by 2100) are analyzed, as shown in the papers by Riahi et al., and Keppo et al.

Against this broader background, additional specific uncertainties are explored in more detail in individual papers in this Special Issue. These include uncertainties in the climate response to GHG emissions and concentrations, and their implications for attaining specific climate change targets, as in the paper by Keppo et al.; implementation uncertainties such as the participation in international climate polices, as in the paper by Keppo and Rao; and uncertainties associated with potentials, costs and deployment of mitigation options, as in the papers by Riahi et al. and Rokityanskiy et al. Another important uncertainty is associated with place-specific and regional interpretations of the scenarios and their driving forces. Here a novel feature reported in this Special Issue is a high spatial resolution of population and economic development paths of the scenarios, as presented in the paper by Grubler et al. This is in stark contrast to the customary global and world-region perspectives of long-term scenarios. The high spatial resolution of driving forces facilitates the assessment of uncertainties associated with both impacts of climate change as well as response strategies.

A number of common threads connect all papers in this Special Issue. The first one is that all analyses are based on a common set of comparable scenarios. This is in contrast to most of the climate change literature that continues to be plagued by a plethora of different scenarios used in the various assessments making a comparison of consistent model results almost impossible. The second common thread of all papers in this Special Issue is that they all report on various aspects of an overall integrated methodological framework, the IIASA Integrated Assessment Modeling Framework as described in the paper by Riahi et al.

The common analytical framework of all papers encompasses detailed representations of the principal GHG-emitting sectors — energy, industry, agriculture, and forestry, combining a careful blend of rich disciplinary models that operate at different spatial resolutions. The different models are solved iteratively in order to balance prices and quantities exchanged across sectors, as well as, in order to achieve consistent cross-scale linkages, making the scenarios and analyses internally consistent. This kind of iterative coupling of the models that represent the energy, agriculture, and forestry sectors takes into account consistently all GHGs and their respective mitigation potentials and also accounts for important feedbacks and interdependencies between sectors. As an example for the need for such model linkages consider the competition for land among sectors as exemplified in the consistent treatment of biomass energy, as reported in the paper by Riahi et al., and of forest sequestration potentials, as in the paper by Rokityanskiy et al. Likewise, impacts of climate change are endogenous in the scenarios reported here, for example, in terms of changes in agricultural production and gross domestic product (GDP) due to a changing climate, as analyzed in the paper by Tubiello and Fischer, or in the corresponding changing irrigation needs for agricultural production, as examined in the paper by Fischer et al. Finally, the scenarios also incorporate previously under-explored mitigation options, such as the use of biomass in conjunction with carbon sequestration and storage (CSS) that could result in an artificial "sink" for anthropogenic CO_2 emissions, in addition to forest sinks.

This Special Issue has the following structure. The first three papers (Riahi et al., Keppo et al., Keppo and Rao) begin the analytical cycle by introducing the scenarios common to all papers. They also provide a synthesis for the sectoral perspectives with a particular focus on mitigation technology portfolios (Riahi et al.), probabilistic analysis of climate change uncertainty on mitigation strategies (Keppo et al.), and implications of regional non-compliance on mitigation efforts, costs and feasibility of meeting climate stabilization targets (Keppo and Rao). The next four papers (Grubler et al., Tubiello and Fischer, Rokityanskiy et al., and Fischer et al.) address the issues at a much finer level of spatial detail, required especially for the analysis of land-based managed ecosystems such as agriculture and forestry. Grubler et al. present the methodology developed to generate spatially explicit interpretations of main scenario drivers that serve as the analytical backbone to achieve cross scale consistency across the spatially-explicit and world-regional models within the integrated assessment framework. Tubiello and Fischer address the important issue of climate change impacts on agriculture and resulting vulnerabilities (people at risk of hunger). Rokityanskiy et al. analyze the potential of world forests to sequester CO_2 under a range of carbon price scenarios with a new, spatially explicit modeling framework, whose results feed back into the overall modeling results presented by Riahi et al. In a similar way, also the detailed results of Tubiello and Fischer also feed back into the integrated modeling framework and the results summarized by Riahi et al. Finally, Fischer et al., complete the climate change analytical cycle (emissions–impacts–mitigation) by looking also at adaptation to climate change taking agricultural water and increasing irrigation needs as an example.

3. Overview of paper one: "Scenarios of long-term socio-economic and environmental development under climate stabilization"

The first paper in this Special Issue by Keywan Riahi, Arnulf Grubler and Nebojsa Nakicenovic "Scenarios of Long-term Socio-economic and Environmental Development under Climate Stabilization" presents an overview of the GHG emissions scenarios for the twenty-first century, which form the analytical backbone for other contributions to this Special Issue. Considering that climate change unfolds slowly and that the global energy and agricultural systems may be restructured only over decades, the 100-year time horizon of the analysis is apt, though evidently fraught with deep uncertainties. Thus, Riahi et al. explore a set of alternative future developments (or scenarios) that are based on a wide range of qualitative and quantitative assumptions in order to bracket the "upstream" uncertainties associated with the drivers of future GHG emissions, the magnitude of ensuing climate change, the associated uncertainties in climate impacts and vulnerability, and finally the feasibility and costs of emission mitigation measures. The scenarios are grouped into "baseline" scenarios (the scenarios A2r, B2, B1 are derivatives of scenarios developed earlier for the IPCC Special Report on Emissions Scenarios (SRES)) that aim to elucidate these uncertainties in the drivers and the resulting emissions outcomes that a century-long perspective necessarily entails, along with so-called "intervention" or climate policy scenarios that are built on the "baseline" scenarios and are used to explore feasibility and costs of climate stabilization measures. In total 11 "stabilization" scenarios are analyzed, offering plausible interpretations of the stated objective of the United Nations Framework Convention on Climate Change (UNFCCC) "stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC Art. 2).

Riahi et al. explore the implications of baseline and target uncertainties on the choice of individual technology options and appropriate (technology) portfolios of emissions abatement measures, in particular with respect to their aggregated cumulative emissions reduction over the twenty-first century as well as their deployment over time. Ultimately, stabilization of GHGs at relatively low levels requires a complete restructuring of the global energy system over the course of the century.

The authors also break new ground in their robust analysis of technology portfolios. Their findings have direct policy relevance for R&D and technology deployment policies that frequently lack the analytical basis to transgress "let 100 flowers bloom" strategies — a too often least common denominator of vested institutional interests that in view of limited resources frequently results in sub-critical funding levels almost across the board. Among others, their analysis suggests that a narrow focus on supply-side mitigation options alone is likely to fall short of harnessing the full synergistic mitigation potential of new technologies that could result from integrating both energy end-use (efficiency) and supply aspects.

Another important conclusion from the analysis is that aggregated macroeconomic costs of climate mitigation are relatively modest, especially when compared to the long-term growth of economic activity as described by even the most pessimistic scenarios. Nonetheless, climate mitigation has important economic implizcations for individual sectors, generating both winners and losers. Stringent climate change mitigation efforts can change significantly the relative economics of traditional versus new, more climate friendly products and services. This is especially the case within the energy system, which accounts for the largest share of emissions reductions, but it is also the case in the agriculture and forestry sectors, where emissions reduction and sink enhancement measures are comparatively more modest. Nonetheless, emission reductions or GHG sink enhancements in these sectors could in the long term rival the value of traditional agricultural and forestry products indicating a possible drastic redefinition and enlargement of the economic basis of these primary sectors in the direction of providing in addition to food, fiber, and wood products also environmental services.

4. Overview of paper two: "Probabilistic temperature change projections and energy system implications of greenhouse gas emission scenarios"

The next paper by Ilkka Keppo, Brian O'Neill, and Keywan Riahi "Probabilistic Temperature Change Projections and Energy System Implications of Greenhouse Gas Emission Scenarios" extends the above "upstream" uncertainty analysis "downstream" to the climate change uncertainty chain, connecting changes in human activities to climate change impacts, and treats a discrete variable, the so-called climate sensitivity, in probabilistic terms. The climate sensitivity is defined as the equilibrium global mean temperature change resulting from an increase of the CO_2 concentration to twice its pre-industrial level, thus linking radiative forcing pathways to climate outcomes. Due to this role the climate sensitivity is of paramount importance for assessing the potential benefits of mitigation policies in terms of avoided damages. Yet, not only is its precise value unknown, but there is disagreement on the quantification of its uncertainty as well. Thus, achieving a given concentration target by constraining emissions will only achieve a given temperature outcome with a certain degree of likelihood, and this likelihood itself is uncertain.

Using recently published estimates of probability density functions of the climate sensitivity, Keppo et al. translate emission scenarios into probabilities for climate change and, by repeating this for a whole range of scenarios and thus taking into account baseline and stabilization uncertainties, arrive at likelihoods of meeting predefined climate stabilization targets. The paper confirms that the likelihood of staying below given temperature targets largely depends on the underlying socio-economic developments in the baseline scenarios. If temperature targets are set low, a low emission baseline (i.e., in absence of climate policies) development can even be considered a requirement for reaching these targets in the first place. This result highlights an important extension of climate policy considerations in direction of other “no or least regret” policy options, frequently associated with sustainable development concepts, and thus reconfirms the findings of the Riahi et al. scenario paper introduced above. Even more importantly, reducing emissions not only increases the probability of meeting given temperature targets, but also reduces the uncertainty of future warming. From this perspective the paper offers an important revision to the traditional perception that reductions in the (vast) uncertainties surrounding climate change solely depend on progress in basic science: in fact, climate policy and ensuing emission reductions are an important additional strategy for reducing uncertainties in the levels and rate of future global warming.

A distinguishing feature of the paper is that it extends the probabilistic analysis framework by considering in addition to absolute levels of climate change also rate changes. Rate change, defined as the rate of change per decade in the radiative forcing or temperature, is an important indicator for assessing the possibility of adapting to a changing climate, in particular of a natural eco-system, whose ability to adapt is limited. It is important to consider this aspect because two scenarios with similar probabilities of reaching an absolute long-term temperature target can differ in their likelihood of exceeding a rate target: e.g., a baseline scenario that is already favorable to climate regimes is less likely to cause peaks in rates of temperature change.

From their analysis of medium-term characteristics of the scenarios, the authors conclude that the chances of meeting a particular long-term temperature target cost-effectively is strongly dependent on the pace at which zero-carbon energy can be introduced over the next five decades. This finding has important implications for policy making, since it emphasizes the importance of short-to-medium-term measures as part of a long-term cost-effective climate abatement strategy. The results also highlight the central role of medium-term policies and interim targets in keeping long-term climate stabilization target options open over the next decades. For a century-long time perspective the modeling results also imply that long-term fundamental structural changes of the present fossil-dominated energy system are a necessary but not a sufficient condition for achieving low climate change outcomes. Meeting low temperature targets cost-effectively and at relatively high probabilities requires a wide portfolio of measures, including in particular energy conservation and efficiency improvements, as well as deploying mitigation options in the industry, agriculture and forest sectors. Keppo et al. find that these, predominantly non-CO_2 and non-energy measures, or policy “targets”, generally qualify as lowest medium-term cost options. The resulting required multi-gas multi-sector perspective is addressed in more detail in subsequent papers in this Special Issue.

5. Overview of paper three: “International climate regimes: Effects of delayed participation”

Having covered ground on socio-economic as well as geophysical sources of uncertainty, it must be noted that long-term climate-policy and modeling studies generally assume a “perfect” policy environment in which both policy instruments as well as cooperative behavior of individual parties are assumed to operate with perfect efficiency. This assumption is encoded in the modeling methodology that almost invariably relies on global, social planner optimization models that have been developed for the purpose of global cost–benefit or cost-effectiveness analysis of climate change mitigation. However, the approach neglects the pronounced free-riding incentives and strong economic and environmental asymmetries characterizing the nature of climate change as a common global problem, as well as the heterogeneity of actors and interests. Hence the models generally have difficulties in dealing with “imperfectly” operating policies.

In general, policy models of climate change mitigation generally either assume full “when and where” flexibility (i.e., emissions are reduced when and where they are most cost-effective within an inter-temporal global optimization framework) or alternatively determine regional mitigation and emission paths based on exogenously defined burden sharing rules without real when-and-where flexibility. The paper by Ilkka Keppo and Shilpa Rao “International Climate Regimes: Effects of Delayed Participation” represents an important analytical advance in examining the implementation uncertainties of climate policies while still maintaining the methodological rigor and information provided by cost minimization models.

The paper provides a systematic sensitivity analysis of climate stabilization scenarios as they are affected by varying delays of participation by different regions in emission mitigation efforts. Each variant of non-cooperative behavior has an effect on the feasibility, costs, timing, magnitude, and nature of the mitigation response of all other cooperating regions. The energy-systems optimization model MESSAGE is used to construct several climate change mitigation scenarios with varying regional participation in the short (2030) to medium-term (2060). Comparison of these results to those from a global scenario that assumes full spatial and temporal flexibility as well as full participation throughout the century helps to evaluate how participatory decisions in climate mitigation efforts by individual regions affect the mitigation response as well as costs and technology choices of other regions.

The results of this detailed sensitivity analysis confirm the importance of establishing international climate policy regimes that involve as large a number of regional players as possible right from the beginning. In a cost-optimizing model with perfect foresight, such as MESSAGE, delayed participation of one region over the short-term (to 2030) generally results in participating regions postponing their own mitigation. A robust finding from the systematic sensitivity analysis is the fact that over longer-time periods, e.g., to 2060, climate stabilization at reasonable low targets requires almost complete participation, especially from the largest emitting regions in Asia (China and India). Over the long-term, unless the baseline scenario emissions are comparatively low and the stabilization target is modest, “free riding” or non-participation of almost any of the regions in climate mitigation efforts will jeopardize global stabilization.

Keppo and Rao conclude that non-participation in global mitigation efforts results in a hefty economic penalty: mitigation costs increase substantially with the degree of non-cooperative behavior with the scale of the economic penalty depending on the baseline emissions, contribution of the non-participating region to the global emissions burden, the stringency of the climate target, and the spatial and technological flexibility assumed in the reorganization of mitigation measures from other regions that need to make up for the “shortfall” in emission reductions due to a region’s non-compliance. Another interesting finding is that non-participation leads to additional inertia in energy systems and thus to a delayed “technological transition” towards a low-carbon future. This “lagging behind” in technology and infrastructure development is the inevitable long-term economic trade-off entailed by the short-term economic benefits of “free riding” by non-participation in globally coordinated mitigation efforts.

6. Overview of paper four: "Regional, national, and spatially explicit scenarios of demographic and economic change based on SRES"

The central theme of this Special Issue, uncertainty in climate change, has other important aspects in addition to those introduced so far. Spatial heterogeneity of potential impacts and mitigation potentials is particularly important for both the agriculture and the forest sectors. It is thus also appropriate to highlight that spatial (dis-)aggregation and cross-scale linkages are important additional sources of uncertainty in the analysis of climate change. This insight that climate change uncertainty systematically increases at lower spatial scales was previously gained by detailed analysis of the results of General Circulation (climate) Models (GCMs): even for comparable levels of global warming (increase in global mean temperature), regional implications vary enormously ranging from local cooling to warming, or from more to less precipitation, etc. This variability and uncertainty at the regional level is amplified by the additional uncertainty arising from comparing results from different GCMs at the regional/local level for comparable global climate change scenarios.

The paper by a large interdisciplinary team comprised by Arnulf Grubler, Brian O'Neill, Keywan Riahi, Vadim Chirkov, Anne Goujon, Peter Kolp, Isolde Prommer, and Erik Slentoe on "Regional, National, and Spatially Explicit Scenarios of Demographic and Economic Change Based on SRES" represents a quantum leap in both the methodological and empirical aspects of the nascent field of spatially explicit scenario and climate change analysis. The paper not only illustrates the importance of looking at spatial heterogeneity; but also offers new approaches and methodologies for capturing this heterogeneity in dynamic socio-economic scenarios, which to date have invariably either ignored spatial detail, or relied on (entirely implausible) assumptions of uniform proportional spatial growth patterns.

The paper by Grubler et al. reports on an exercise in developing spatially explicit scenario interpretations for population and economic activity for the three scenarios introduced in the Special Issue's Riahi et al. paper. Using a combination of decomposition and optimization techniques a number of scenario indicators that are originally developed at the level of 11 world regions are first "downscaled" to the level of 185 countries and subsequently to the level of grid cells at a resolution of 0.5 by 0.5 degrees. The spatially explicit scenarios also explicitly account for urbanization and rural–urban income differences which are treated as scenario-dependent variables. The spatially explicit scenarios fulfill a dual role in the integrated scenario uncertainty analysis reported in this Special Issue. First, they elucidate an important additional uncertainty dimension to the climate change problem which arises from spatial heterogeneity, perhaps best illustrated by the staggering urban growth in developing countries that characterizes invariably all scenarios despite the vast differences in their assumed population growth and urbanization rates. Second, the scenarios provide important input data for the spatially explicit modeling of land-based GHG emission mitigation options such as biomass energy and carbon sequestration options (e.g., afforestation) that are reported in the three subsequent papers concluding this Special Issue (Rokityanskiy et al., Tubiello and Fischer, and Fischer et al.). As such the spatially explicit scenarios fulfill an important bridging function linking global and world regional "top down" with place-based modeling perspectives that are needed for the assessment of land-based sectors, such as agriculture and forestry. The spatial detail also allow a closer look on issues of competing land-use and thus, in the case of bioenergy, provides for a much more realistic – albeit substantially lower – assessment of the mitigation potential of this option, compared to the global assessments that have dominated the climate mitigation literature to date.

The paper by Grubler et al. provides key findings that are also of wider interest beyond the climate change universe. For instance, the paper highlights the importance of the persistence of urban clusters in industrialized countries (as well as Latin America) combined with a vast potential for megacity (Africa) and urban corridor (Asia) growth in developing countries. The paper suggests that developments in Asia will be particularly dramatic over the next five decades with an unprecedented scale of emerging urban agglomerations in terms of population and economic activities that could surpass many-fold the currently most dense urban corridors, such as Boswash in the USA or Shinkansen in Japan. Grubler et al. emphasize the need for new infrastructure "backbones" along urban clusters rather than networks of "island" cities, particularly in the Asian urbanization "hotspots" of Bengal and the Chinese coast.

The next three papers, concluding this Special Issue illustrate the importance of detailed, spatially explicit assessments of climate change, taking into account the diversity of local natural and socio-economic conditions that will determine the extent of climate change impacts, potentials for mitigation, as well as feasibility and costs of adaptation measures to a changing climate. Of all sectors, agriculture is both most sensitive to a changing climate and also in greatest need of adaptation. Therefore two papers in this Special Issue are devoted to agriculture analyzing both climate impacts (Tubiello and Fischer) as well as possible adaptation strategies (exemplified through irrigation in Fischer et al.). The agricultural sector together with forestry, however, also offer significant potentials for mitigation. Whereas the agricultural mitigation options have been analyzed previously (Riahi et al.), and are not reported separately again in this Special Issue, forestry mitigation through carbon sequestration (avoided deforestation as well as afforestation) has to date been analyzed largely through a sectoral perspective without due regard to its interdependencies with the energy and agricultural sectors, in particular with respect to land-use constraints and conflicts. Therefore, a separate paper (Rokityanskiy et al.) is devoted to this topic in this Special Issue. Given the size and complexity of the related agricultural and forestry models only selected scenarios could be calculated for the integrated assessment analysis reported here. Therefore the analysis of agricultural impacts and adaptation focuses on contrasting a "worst case" scenario combining high climate change with high demand for agricultural products (the A2r scenario) with a similar scenario of high demand but with lower climate change (due to mitigation). The forestry sector analysis conversely focuses on the two extreme scenarios A2r and B1 to bracket the uncertainties of forest carbon sequestration potentials ranging from low (A2r) to high (B1). The three papers do not explore intermediary developments in either socio-economic or climate change, nonetheless, combined they provide important analytical insights into the uncertainty "boundaries" framing the climate change policy debate.

7. Overview of paper five: "Reducing climate change impacts on agriculture: Global and regional effects of mitigation 2000–2080"

From all concerns about climate change and its variability, the impacts on agricultural production are worldwide the most widespread. For one, food security is prominently on the list of human activities and ecosystem services under threat of dangerous anthropogenic interference through the climate system. Secondly, each country is naturally concerned with potential damages and benefits that may arise over the coming decades from climate change impacts on its territory as well as globally, since these will affect domestic and international policies, trading patterns, resource use, regional planning, and therefore the welfare of its people in terms of food security and prices of agricultural products.

The paper by Francesco Tubiello and Günther Fischer on "Reducing Climate Change Impacts on Agriculture: Global and Regional Effects of Mitigation 2000–2080" provides an important analytical advance by complementing traditional climate impacts analysis by also examining in detail the effects of reducing possible climate change through mitigation measures. As such, the paper fulfills an important role in giving quantitative estimates of the benefits of climate mitigation using climate sensitive agriculture as the prominent example. In terms of the central uncertainty theme underlying this Special Issue, Tubiello and Fischer highlight in particular the additional uncertainty entailed when incorporating (different) regional climate change projections derived from alternative GCM runs into their analysis.

The future of world agricultural production is shaped by three interrelated sets of drivers: growth in population and incomes as well as societal change (changing diets), improvements in agricultural crops and technology (yield increases), and finally climate change. The high demand A2r scenario provides a good illustration of the influence of these various groups of variables. For instance due to population, income, and dietary change world demand for cereals could double (to 4.2 Gt) between 2000 and 2080 with agricultural GDP almost tripling over the same time period. With rising yields this agricultural output could basically be sustained based on currently available arable land (1.5 billion ha worldwide). Hence, it appears that in the absence of climate change, available land and crop resources, together with technological progress, could be sufficient to feed a world population approaching 12 billion people towards the end of the twenty-first century. Nonetheless, even with this positive picture, people exposed to the risk of hunger could still amount to above half a billion by 2080 – representing though a reduction from some 800 million at risk of hunger in the year 2000 – all in developing countries. These results already indicate that a simple global perspective would mask persistent regional heterogeneity, ranging from overabundance to penury at the national and sub-national levels.

Climate change adds to this heterogeneity, amplifying disparities between highly productive (and adaptive) agricultural systems and less productive, more vulnerable ones. Current research confirms that while crops could respond positively to elevated CO_2, the associated impacts of high temperatures, altered patterns of precipitation, and possibly increased frequency of extreme events (such as drought and floods) taken together would result in depressed yields and increased production risks in many world regions. This could lead to a widening of the gap between rich and poor countries, in particular, given also the fact that developing countries are more vulnerable to climate change than developed countries (because of the predominance of agriculture in their economies, the scarcity of capital for adaptation measures, their often warmer baseline climates, and their heightened exposure to extreme events). Under the projected climate change, even in the more extreme A2r scenario for instance, global impacts on agricultural production do not appear particularly daunting with a loss in global agricultural production and GDP of at most one percent respectively. These results confirm earlier analyses that even in the most sensitive sectors exposed to climate change, such as agriculture, baseline uncertainties (future growth in demand, crop yields, and international trade regimes for agricultural products) by far outweigh the uncertainties of climate change.

It is however more instructive to look at the regional results rather than global numbers, as aggregates necessarily balance both winners and losers of climate change. For temperate regions in the industrialized world, Tubiello and Fischer conclude that climate change impacts are either positive or only slightly negative. Their results for 2080 suggest a benefit of some 0–25 billion US$ for all industrialized countries and a loss of some 30–50 billion US$ for developing countries taken together. Conversely, impacts on individual developing regions are substantially larger (and also more variable): the biggest losers would be sub-Saharan Africa with projected losses in agricultural GDP of between 15 to 40 billion US$, followed by the Indian subcontinent with losses ranging from 10 to 20 billion US$ (compared to estimated benefits of climate change for Latin America of between 12 and 25 billion US$). People at risk of hunger could increase due to climate change by some 70–90 million with most of that increase occurring in sub-Saharan Africa (43–53 million), followed by the Middle East and North Africa (14–20 million more at risk of hunger).

Stabilization of climate at an illustrative (intermediary) target of some 670 ppmv-equivalent would mitigate almost all of the above negative climate change impacts on agriculture. This result is of particular significance for those seeking to define levels of "dangerous interference with the climate system", provided of course that climate change would indeed proceed gradually without big, non-linear effects. For instance the projected agricultural GDP loss of up to 50 billion US$ due to climate change could be turned into a benefit of above 30 billion US$ for the developing countries considered together. More importantly, the negative consequences of climate change on the most vulnerable regions (Africa and India) could be entirely mitigated (even turned into a small benefit) and the number of additional people at risk from hunger reduced from 70–90 million to 3–14 million by 2080. These positive developments have, however, also to be contrasted with the findings that climate mitigation in turn could produce also losers, particularly for large crop exporting in temperate-zone developed countries. The economic benefits of climate mitigation on world agriculture are projected to amount to some 10–30 billion US$, or between 72 and 99% of the projected losses due to climate change in an unmitigated scenario. Humanitarian savings of mitigation, in terms of the reduced number of people at risk of hunger, are estimated at 30–60 million people (compared to a baseline of 555 million) representing a reduction by 60–85% of the additional numbers of people at risk of hunger due to unmitigated climate change, about two-thirds of this reduction being realized in Africa. To put these mitigation benefit numbers into perspective: they compare to some 12 billion US$ mitigation costs (due to emission reduction measures) in the agricultural sector (and to some 2 trillion US$ for all sectors taken together). The good news is that from a cost–benefit consideration, climate mitigation in the agricultural sector compares favorably. The bad news is of course that due to the small size of the agricultural sector in the overall economy in the twenty-first century, the sectoral benefits of mitigation are small indeed compared to the total economy-wide mitigation costs, which suggests the need to look analytically into climate mitigation benefits in other sectors as well. The results presented for agriculture in Tubiello and Fischer sketch the methodological direction for such studies.

8. Overview of paper six: "Geographically Explicit Global Modeling of Land-use Change, Carbon Sequestration and Biomass Supply"

Next to agriculture, forests are the second most important managed ecosystem both affected by climate change as well as by its mitigation. Contrary to agriculture, the modeling/assessment of forest impacts and mitigation options in climate stabilizations scenarios has to date largely been based on modeling of biophysical phenomena (e.g., climate, precipitation, soil quality) with little regard to economic drivers such as competing land-uses (agriculture, biomass plantations, or forestry) or changing land prices. A prime motivation of the integrated assessment reported in this Special Issue was, therefore, to improve upon the methodological state of art of modeling of land-based GHG emission mitigation options such as biomass energy and carbon sequestration options (e.g., afforestation).

The paper by Dimitri Rokityanskiy, Pablo C. Benìtez, Florian Kraxner, Ian McCallum, Michael Obersteiner, Ewald Rametsteiner, Yoshiki Yamagata "Geographically Explicit Global Modeling of Land-use Change, Carbon Sequestration and Biomass Supply" responds to the above methodological challenge by developing a new model, the Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA) model that generates spatially-explicit and scenario-specific projections on the impacts of forestry-related carbon sequestration policies (e.g., those that discourage deforestation, promote afforestation, or provide incentives for bioenergy supply from forests). The model helps in particular to quantify the economic potential of forests under climate mitigation, modeling specifically the interactions and feedbacks between ecosystems and anthropogenic activities. The model generates 100-year scenarios of land use change, carbon sequestration, impacts of carbon incentives, biomass for bioenergy, and climate policy impacts on forest at a 0.5 by 0.5 degrees spatial resolution.

In comparison with the large number of studies and surveys of carbon sequestration costs the DIMA model approach includes a number of novel features. Firstly, it couples downscaled data specific for each of the scenarios examined (Grubler et al. in this Special Issue) with the dynamic development of climate policy implications (including carbon and bioenergy prices) as calculated by the coupled energy systems model MESSAGE (Riahi et al. in this Special Issue). In addition, DIMA takes also the results of the urbanization scenarios underlying the scenario downscaling exercise (Grubler et al.) as well as the agricultural developments (Tubiello and Fischer in this Special Issue) into account. Land-use change decision making rules are for instance constrained by guaranteeing food security and sufficient land for urban development along the scenario trajectories as calculated by the other models of the integrated assessment framework. Comparable analysis to date has either focused in the global or mostly at a continental or sub-continental scale.

The DIMA modeling results indicate that carbon sequestration policies – such as those that promote afforestation and discourage deforestation (i.e. avoided deforestation) – could contribute significantly to a global portfolio of efficient climate mitigation policies. The size of forest-related emissions mitigation will evidently depend on prevailing carbon prices. Overall, the total carbon sequestration supply from forests (until 2100) could reach 200 GtC (equal to about 120 years of today's net land-use or to some 30 years of current energy-related emissions). The vast majority of this volume comes from tropical forests, including 34% sequestered in South America and 26% in Africa in an illustrative A2r scenario with stringent climate policies. Results from DIMA show also that the share of globally avoided deforestation would grow exponentially with rising carbon prices. As such, climate mitigation policies and their implied "carbon price value" could indeed serve as the most important leverage for conserving tropical forests.

The model results also indicate that if, indeed, modern biomass technologies would play a significant role under climate stabilization efforts, global terrestrial landscapes will face unprecedented land-use changes which are highly sensitive to future carbon prices. The estimated carbon sequestration costs are generally in the same range or lower than those of carbon abatement measures in the energy system, suggesting that forest-based carbon sequestration merits attention as a cost-effective climate mitigation strategy, albeit its absolute potential is evidently limited. The results indicate also that in addition to cost effectiveness, carbon mitigation policies could yield substantial co-benefits, both in terms of avoided tropical deforestation as well as in terms of economic opportunities opened to rural communities. These benefits could be substantial particularly in Africa or Latin America, because of their strong comparative economic advantage in forest based bioenergy supply and afforestation.

9. Overview of paper seven: "Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080"

The analysis of climate change has, to date, predominantly focused on the estimation of climate change-induced impacts, including measures to avoid impacts through mitigation (i.e., emissions reductions). Adaptation to climate change, which is learning to live with climate change and instituting measures to facilitate adapting to a changing environment, has so far received less attention. Adaptation is though of particular importance as due to the inertia of the climate system and the already "committed" climate change signal embedded in past, present, and near-term emissions, a certain degree of climate change will be inevitable. Some climate change is also inevitable, irrespective of the scale and success of climate mitigation policies implemented, as those are only beginning slowly to emerge and will – as indicated in the stabilization scenarios analyzed in this Special Issue – even in the best of all worlds take many decades to unfold before reducing the expected global warming signal.

It is therefore appropriate that the last contribution to this Special Issue examines adaptation to climate change. The sector examined is again agriculture. Thus, the analysis complements the previously presented impact assessment with estimations for adaptation. An important feature of the adaptation analysis is that it departs from the traditional so-called "dumb farmer" scenarios (where a future climate is suddenly imposed on today's agricultural systems in the model calculation). The methodology considers a range of "soft" adaptation measures such as changing planting and crop patterns (and which is among the reasons the projected impacts of climate change on agricultural production reported by Tubiello and Fischer above are substantially lower than older estimates). The paper by Günther Fischer, Francesco Tubiello, Harry van Velthuizen, and David Wiberg "Climate Change Impacts on Irrigation Water Requirements: Effects of Mitigation, 1990–2080" examines an important – albeit capital and resource intensive – adaptation option for agriculture: increasing irrigation.

Globally about 18% (270 million ha) of cultivated land is irrigated. Agriculture is the largest user of water among human activities accounting for 70% of the total anthropogenic use of renewable water resources — about 2630 billion m^3 yr^{-1} out of 3815 billion m^3 yr^{-1}. Irrigated crops produce about 40% of total agricultural output; their yields are typically twice the yields of rain fed crops. Given that, to date, little research has examined the climate change implications on irrigation water needs, the paper by Fischer et al. represents an important analytical advance. The paper employs biophysically and agronomic-based hydrology computations within a spatially detailed agro-ecological zone assessment model to assess the water irrigation needs of an illustrative high demand scenario (A2r, identical to the one also analyzed in the Tubiello and Fischer contribution). Moreover, Fischer at al. estimate the associated climate change impacts, and the implications of an illustrative climate stabilization scenario aiming at reducing significantly adverse (irrigation-related) climate change impacts.

In the base case model calculations from Fischer et al. net water demand of irrigated crops (i.e. the amount of water needed for irrigation of crops excluding water losses during water provision) is projected to increase by 45%, from 1350 billion m^3 in 2000 to over 1960 billion m^3 water worldwide by 2080. However, because irrigation efficiency would also increase by some 20% agricultural water withdrawals would only increase by 25%, from 2630 billion m^3 water in 2000 to about 3280 billion m^3, which is an increase of some 650 billion m^3 by 2080 in the baseline scenario without climate change. The projected climate change associated with the baseline scenario would increase global water withdrawal by an additional 670–725 billion m^3 as agriculture needs to adapt to a changing climate. Two-thirds of the increase is due to an increase in daily water requirements under higher temperatures (accounting for 75–80% of climate-induced irrigation demand increases in developing countries, but only 50–60% in developed countries), one-third occurs because of extended crop calendars in temperate and sub-tropical zones.

The significance of this result can best be judged that it is the only area from all aspects of the climate problematique analyzed in this Special Issue, where a changing climate yields a similar influence on resource use as overall socio-economic development. In other words, in this case climate change uncertainty is of similar order of magnitude as socio-economic development or baseline uncertainty. In all other cases (e.g., agricultural production, energy use, or economic activity) uncertainties in future developments of population, economy, or technology have a far greater impact than climate change proper.

To put this climate change impact into perspective: the additional irrigation water withdrawal for agriculture due to a warmer climate corresponds to 60% of all current non-agricultural (households and industry) water withdrawals, suggesting enormous pressure and competition on scarce water resources between expanding human populations and industrial activities and the additional needs for agriculture in order to adapt to a changing climate. Climate change mitigation could reduce some of this pressure by some 125–160 billion m^3. Consequently, mitigation could also reduce the costs of additional irrigation needs due to climate change from some 24–27 billion US$ to some 8–10 billion US$ annually by 2080 according to the calculations by Fischer et al. More importantly, climate mitigation could help to reduce significantly projected water scarcity. Using a weighted water scarcity index to measure regional water scarcity in relation to agricultural water demand, Fischer et al. find that climate mitigation could significantly improve water supply security in the already water-critical Middle East region. It may also improve water scarcity in South Asia, where changes in monsoon precipitation may amplify seasonal water scarcity significantly under unabated climate change.

10. Concluding remarks

Together the seven papers provide an account of new methodological and analytical results achieved within IIASA's Greenhouse Gas Initiative. By doing so, they also provide an overview of the current state of the art of climate change assessment, a field that certainly will continue to evolve as – despite all the uncertainty – climate change will remain to be a major planetary concern on both the scientific and policy agendas.

The authors would like to thank IIASA, its Director Leen Hordijk and the IIASA Council, for the support of the Greenhouse Gas Initiative and the associated research activities. The very useful and critical comments and suggestions of ten anonymous reviewers are especially appreciated. This Special Issue would not have been possible without their dedicated and voluntary efforts. Last but certainly not the least, the authors are grateful for the editorial support of John Ormiston, Kathryn Platzer, and Iain Stewart, the production assistance of Katalin David and for helpful advice and general support by Hal Linstone, Editor in Chief of the Journal.